Celebrating Maria Goeppert twice: nuclear shell model and $\beta\beta$ decay

Javier Menéndez

University of Barcelona
Institute of Cosmos Sciences

Celebrating 75 Years of the Nuclear Shell Model
and Maria Goeppert-Mayer

Argonne National Laboratory, 20th July 2024

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Collaborators

Universitat de Barcelona — **D. Castillo, P. Soriano**

TRIUMF — **L. Jokiniemi**

The University of North Carolina at Chapel Hill — **B. Romeo**

N. Shimizu

Los Alamos National Laboratory, Est. 1943 — **R. Weiss**

Argonne National Laboratory — A. Lovato, B. Wiringa

Technische Universität Darmstadt — **C. Brase**, A. Schwenk

Creation of matter in nuclei: $0\nu\beta\beta$ decay

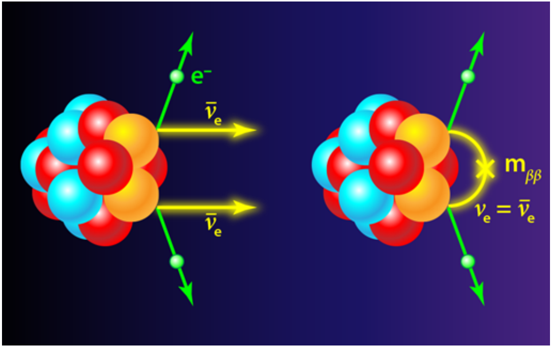
Lepton number conserved
in all processes observed:

single β decay,
$\beta\beta$ decay with ν emission...

Neutral massive particles (Majorana ν's)
allow lepton number violation:

neutrinoless $\beta\beta$ decay
creates two matter particles (electrons)

Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

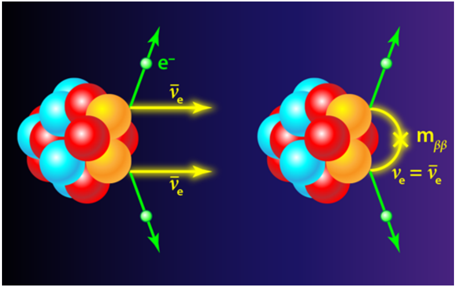


Nuclear matrix elements

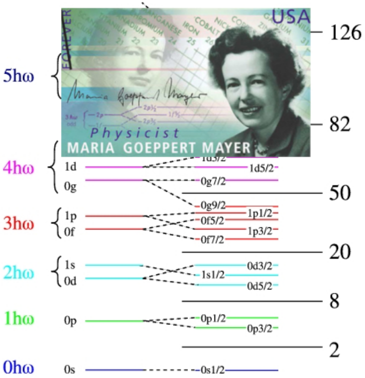
Nuclear matrix elements needed in low-energy new-physics searches

$$\langle \,\text{Final}\, | \mathcal{L}_{\text{leptons}-\text{nucleons}} | \,\text{Initial}\, \rangle = \langle \,\text{Final}\, | \int dx\, j^{\mu}(x) J_{\mu}(x) \,|\, \text{Initial}\, \rangle$$

- Nuclear structure calculation of the initial and final states:
  Shell model, QRPA, IBM,
  Energy-density functional
  Ab initio many-body theory
  QMC, Coupled-cluster, IMSRG...
- Lepton-nucleus interaction:
  Hadronic current in nucleus:
  phenomenological,
  effective theory of QCD



Nuclear shell model



Nuclear shell model configuration space only keep essential degrees of freedom

- High-energy orbitals: always empty
- Valence space: where many-body problem is solved
- Inert core: always filled

$$H\left|\Psi\right\rangle = E\left|\Psi\right\rangle \;\rightarrow H_{eff}\left|\Psi\right\rangle_{eff} = E\left|\Psi\right\rangle_{eff}$$

$$\left|\Psi\right\rangle_{eff} = \sum_{\alpha} c_\alpha \left|\phi_\alpha\right\rangle, \quad \left|\phi_\alpha\right\rangle = a^+_{i1} a^+_{i2} \ldots a^+_{iA}\left|0\right\rangle$$

Shell model diagonalization:

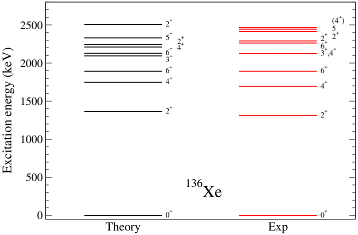
$\sim 10^{10}$ Slater dets. Caurier et al. RMP77 (2005)

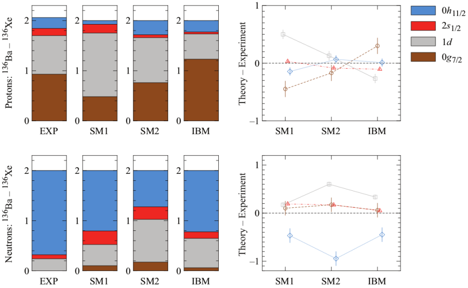
$\gtrsim 10^{24}$ Slater dets. with Monte Carlo SM Otsuka, Shimizu, Y.Tsunoda Phys. Scr. 92 063001 (2017)

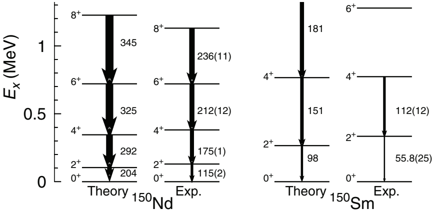
H_{eff} includes effects of

- inert core
- high-energy orbitals

Spectroscopy well described: masses, spectra, transitions, knockout...







Schiffer et al. PRL100 112501(2009)

Kay et al. PRC79 021301(2009)

...

Szwec et al., PRC94 054314 (2016)

Rodríguez et al. PRL105 252503 (2010)

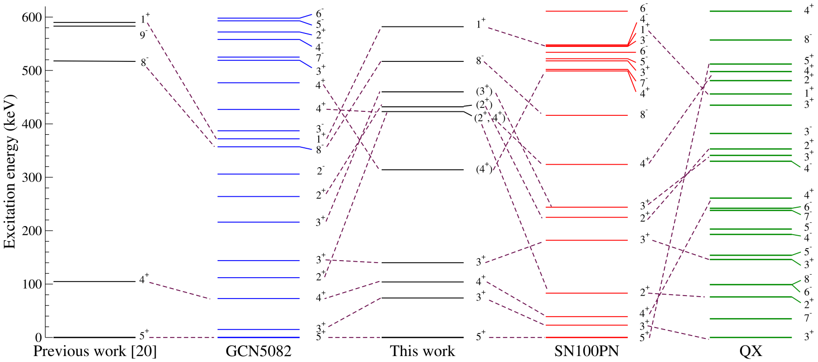
...

Vietze et al. PRD91 043520 (2015)

^{136}Cs experimental spectrum

While all these interactions are well, tested recent data on ^{136}Cs suggests GCN5082 results agree better with experiment than QX

Rebeiro, Triambak et al. PRL131 052501 (2023)

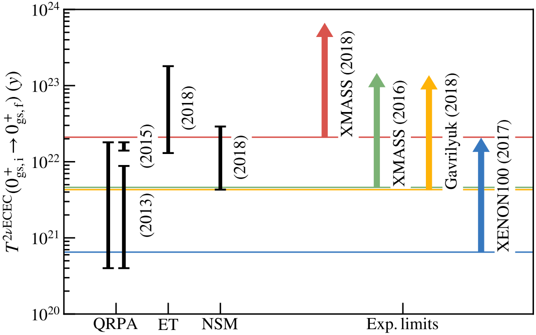


QX systematically smaller ^{136}Xe $0\nu\beta\beta$-decay nuclear matrix elements

Two-neutrino $\beta\beta$ predicted for ^{48}Ca before measurement

Caurier, Poves, Zuker, PLB 252 13(1990)

Recent predictions for 2νECEC ^{124}Xe half-life:
shell model error bar largely dominated by "quenching" uncertainty



Suhonen
JPG 40 075102 (2013)

Pirinen, Suhonen
PRC 91, 054309 (2015)

Coello Pérez, JM, Schwenk
PLB 797 134885 (2019)

Shell model, QRPA and Effective theory (ET) predictions
suggest experimental detection close to XMASS 2018 limit

Two-neutrino ECEC of ^{124}Xe

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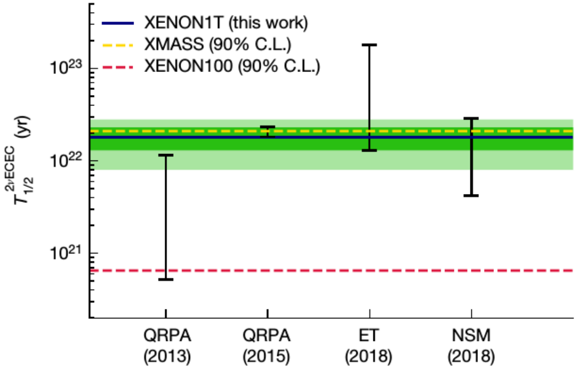

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XENON1T
Nature 568 532 (2019)

Shell model, QRPA and Effective theory (ET) predictions
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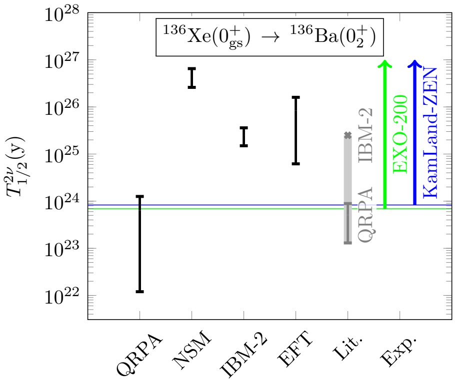
Current experiments sensitive to two-neutrino $\beta\beta$ of ^{136}Xe to ^{136}Ba 0_2^+

EXO-200, KamLAND-Zen



Nuclear shell model
QRPA, EFT and IBM
very different predictions!

Barea et al.
PRC 91 034304 (2015)

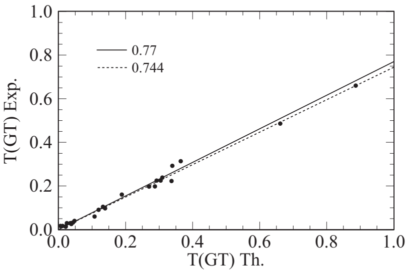
Pirinen, Suhonen
PRC 91, 054309 (2015)

Jokiniemi, Romeo, Brase, Kotila et al.
PLB 838 137689 (2023)

Very good test of theoretical calculations!

Gamow-Teller β decay with IM-SRG

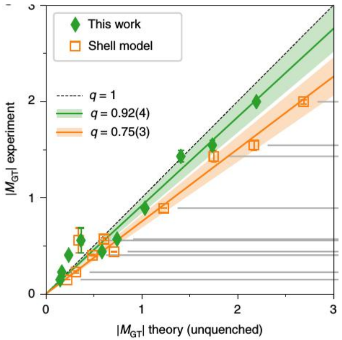
β decays (e^- capture) challenge for nuclear theory



Martinez-Pinedo et al. PRC53 2602(1996)

$$\langle F | \sum_i [g_A \, \boldsymbol{\sigma}_i \tau_i^-]^{\text{eff}} \, | I \rangle \,, \quad [\boldsymbol{\sigma}_i \tau]^{\text{eff}} \approx 0.7 \boldsymbol{\sigma}_i \tau$$

Phenomenological models need $\boldsymbol{\sigma}_i \tau$ "quenching"

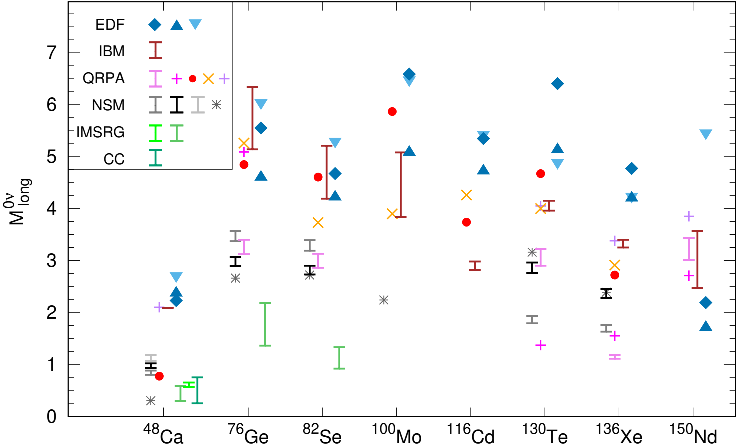


Gysbers et al. Nature Phys. 15 428 (2019)

Ab initio calculations including correlations and meson-exchange currents do not need any "quenching"

$0\nu\beta\beta$ decay nuclear matrix elements

Large difference in nuclear matrix element calculations: factor ~ 3



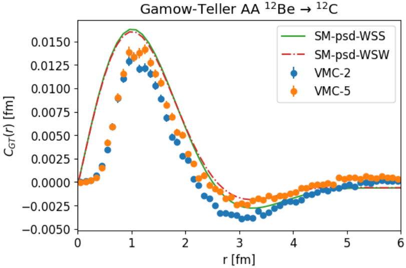
Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

Shell model vs quantum Monte Carlo: correlations

Compare $\beta\beta$ transition densities in
nuclear shell model and quantum Monte Carlo calculations in light nuclei

$$4\pi r^2 \rho_{GT}(r) = \langle \Psi_f | \sum_{a<b} \delta(r - r_{ab}) \sigma_{ab} \tau_a^+ \tau_b^+ | \Psi_i \rangle \qquad M_{GT}^{0\nu} = \int_0^\infty dr\, C_{GT}^{0\nu} \,,$$

Agree at long distances, shell model misses short-range correlations



Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)

Similar findings in Wang et al. PLB 798 134974 (2019)

Generalized contact formalism (GCF)

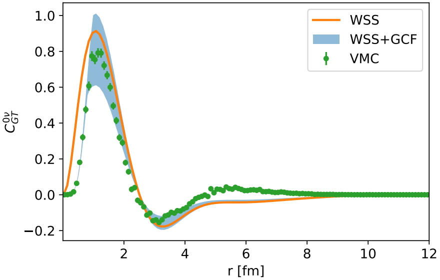
Generalized contact formalism Weiss, Bazak, Barnea, PRL 114 012501 (2015)

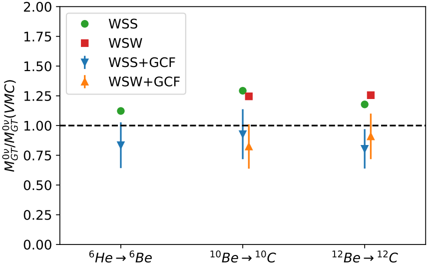
Separation of scales: wf, transition density factorize for nearby nucleons

$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_\alpha \varphi^\alpha(\boldsymbol{r}_{ij}) A^\alpha(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j}), \quad \rho_{GT}(r) \xrightarrow[r\to 0]{} -3|\varphi^0(r)|^2 C^0_{pp,nn}(f,i)$$

The contact $C^0(f,i) = \frac{A(A-1)}{2}\langle A^\alpha(f)|A^\beta(i)\rangle$ is model dependent

Replace shell-model by QMC contact: improve transition density

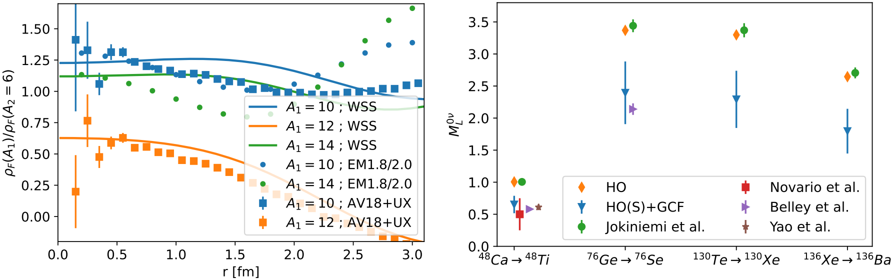




Shell model + Generalized contact formalism

Generalized contact formalism Weiss, Bazak, Barnea PRL 114 012501 (2015)

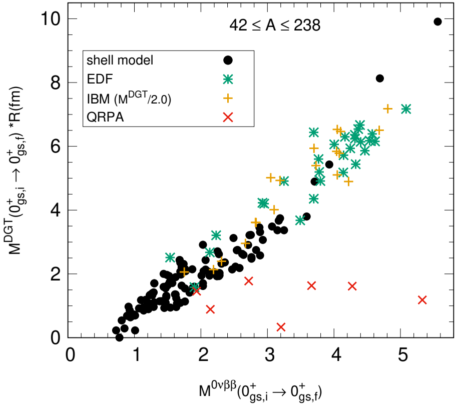
The contact $C^0(f,i) = \frac{A(A-1)}{2} \langle A^\alpha(f)|A^\beta(i)\rangle$ is model dependent
(shell model, quantum Monte Carlo, no-core shell model...)
but the ratio $C^0_{pp,nn}(X)/C^0_{pp,nn}(Y)$ relatively model independent:
QMC in light nuclei + two shell-model calculations: reach heavy nuclei



Good agreement benchmark in light nuclei with ab initio NMEs

Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)

DGT and $0\nu\beta\beta$ decay: heavy nuclei



Shimizu, JM, Yako, PRL120 142502 (2018)

DGT transition to ground state

$$M^{\rm DGT} = \sqrt{B(DGT_-; 0; 0^+_{\rm gs} \to 0^+_{\rm gs})}$$

very good linear correlation
with $0\nu\beta\beta$ decay
nuclear matrix elements

Correlation across wide range,
nuclei from Ca to Ge and Xe

Found in:
nuclear shell model
energy-density functional theory
QRPA
ab initio VS-IMSRG (weaker)

Yao et al. PRC106 014315(2022)
Jokiniemi, JM, PRC 107 044316 (2023)
Wang et al. PLB 855 138796 (2024)

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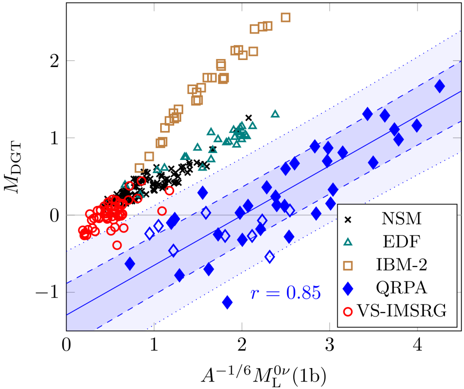

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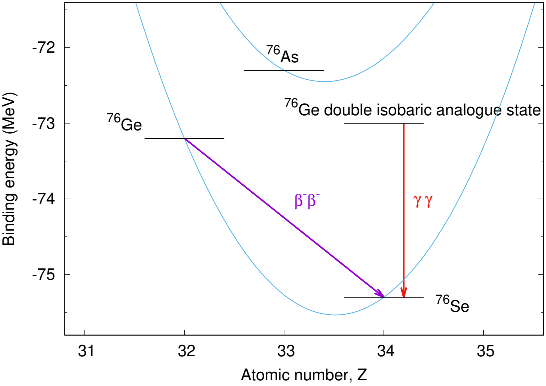
Yao et al. PRC106 014315(2022)
Jokiniemi, JM, PRC 107 044316 (2023)
Wang et al. PLB 855 138796 (2024)

$\gamma\gamma$ decay of the DIAS of the initial $\beta\beta$ nucleus

Explore correlation between $0\nu\beta\beta$ and $\gamma\gamma$ decays,
focused on double-M1 transitions

$$M^{\gamma\gamma}_{M1\,M1} = \sum_k \frac{\langle 0^+_f | \sum_n (g^l_n \boldsymbol{l}_n + g^s_n \boldsymbol{\sigma}_n)^{IV} | 1^+_k(\mathrm{IAS}) \rangle \langle 1^+_k(\mathrm{IAS}) | \sum_m (g^l_m \boldsymbol{l}_m + g^s_m \boldsymbol{\sigma}_m)^{IV} | 0^+_i(\mathrm{DIAS}) \rangle}{E_k - (E_i + E_f)/2}$$



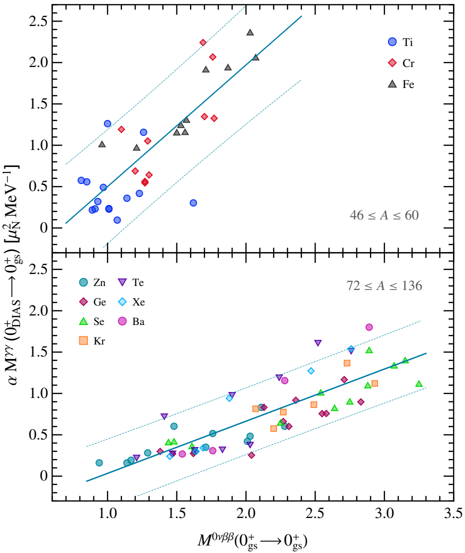
Similar initial and final states
but both in same nucleus
for electromagnetic transition

M1 and GT operators similar,
physics of spin operator
M1 also angular momentum

Different energy denominator

Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

Correlation between $M1M1$ and $0\nu\beta\beta$ NMEs



Good correlation between $M1M1$ same-energy photons and shell-model $0\nu\beta\beta$ NMEs

A dependence:
energy denominator
dominant states at higher energy in heavier nuclei

Overall, study $\sim$ 50 transitions
several nuclear interactions for each of them

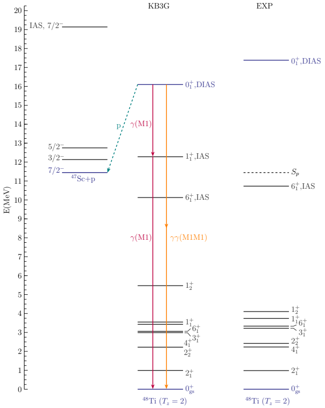
Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

Experimental feasibility of $\gamma\gamma$ decay?

$\gamma\gamma$ decays are very suppressed with respect to γ decays
just like $\beta\beta$ decays are much slower than β decays

$\gamma\gamma$ decays have been observed recently
in competition with γ decays

Waltz et al. Nature 526, 406 (2015), Soderstrom et al. Nat. Comm. 11, 3242 (2020)



Competing decay channels:

Study in detail leading
decay channels for $M1M1$ decay
in DIAS of $\beta\beta$ nuclei

Particle emission $M1$, $E1$ decay:
BR $\sim 10^{-7} - 10^{-8}$

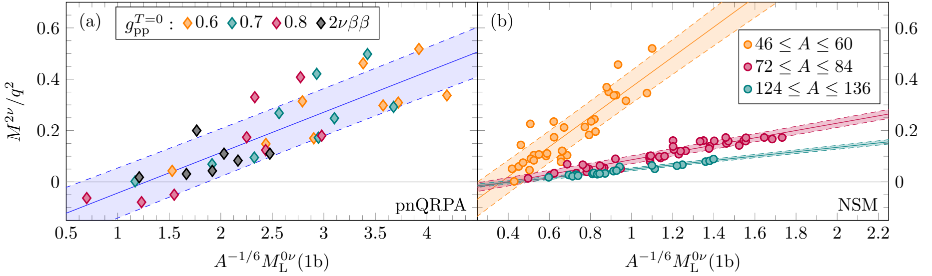
Experimental proposal for ^{48}Ti
by Valiente-Dobón et al.

Romeo, Stramaccioni et al., in prep

Correlation of $0\nu\beta\beta$ decay and $2\nu\beta\beta$ decay

Good correlation between 2ν and 0ν modes of $\beta\beta$ decay
in nuclear shell model (systematic calculations of different nuclei)
and QRPA calculations (decays of $\beta\beta$ emitters with different g_{pp} values)

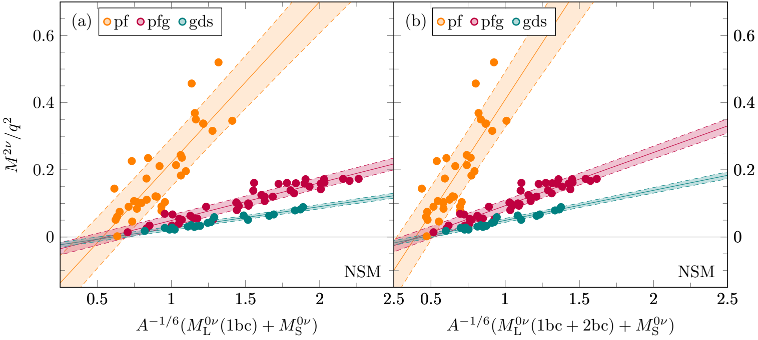
Similar but not common correlation, depends on mass for shell model
$0\nu\beta\beta - 2\nu\beta\beta$ correlation also observed in ^{48}Ca, ^{136}Xe
Horoi et al. PRC106 054302 (2022), PRC107 045501 (2023)



Jokiniemi, Romeo, Soriano, JM, PRC 107 044305 (2023)

Correlation of $0\nu\beta\beta$ decay to $2\nu\beta\beta$: general case

A good correlation between $2\nu\beta\beta$ and $0\nu\beta\beta$
also appears when we include to the calculation of $0\nu\beta\beta$ NMEs
2b currents and the short-range nuclear matrix element

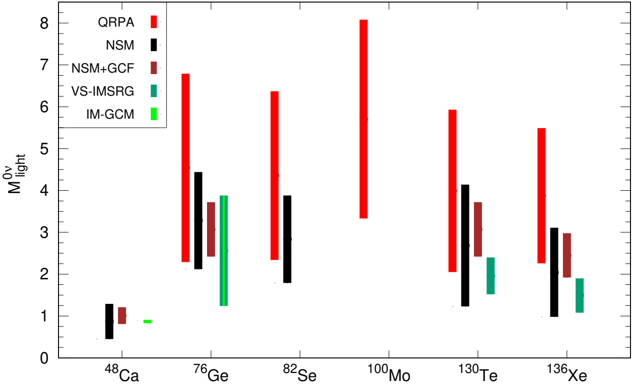


Jokiniemi, Romeo, Soriano, JM, PRC 107 044305 (2023)

Use $2\nu\beta\beta$ data to predict $0\nu\beta\beta$ NMEs with 2b currents, short-range NME

$0\nu\beta\beta$ decay total (long- and short-range) NMEs

Not-so-large difference in nuclear matrix element calculations!



Wirth et al.
PRL127 242502 (2021)

Belley et al.
arXiv:2307:15156

Belley et al.
PRL132 182502 (2024)

Jokiniemi et al.
PRC 107 044305 (2023)

Weiss et al.
PRC106 065501 (2022)

Gómez-Cadenas, Martín-Albo, JM, Mezzeto, Monrabal, Sorel, Riv. Nuovo Cim. 46, 619 (2023)

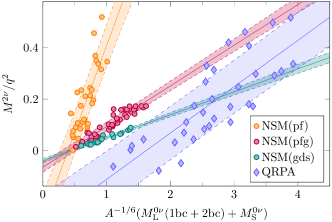
Summary

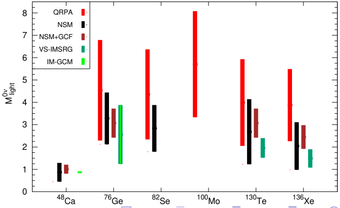
Calculations of $0\nu\beta\beta$ NMEs
challenge nuclear many-body methods,
searches demand reliable NMEs

Individual nuclear spectroscopy
$2\nu\beta\beta$ measurements test many-body methods
used to compute $0\nu\beta\beta$ NMEs

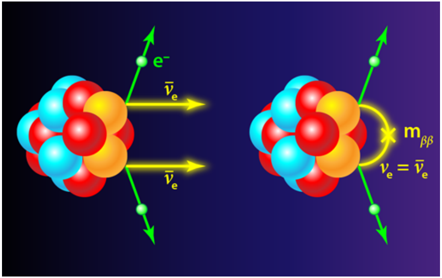
Systematic calculations of
double Gamow-Teller transitions,
electromagnetic $M1M1$ decay of DIAS
good correlation with $0\nu\beta\beta$ NMEs

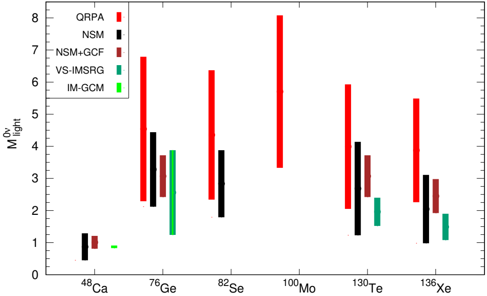
Good $0\nu\beta\beta - 2\nu\beta\beta$ correlation
exploit $2\nu\beta\beta$ data to obtain $0\nu\beta\beta$ NMEs
with theoretical uncertainties





Thank you very much for your attention!



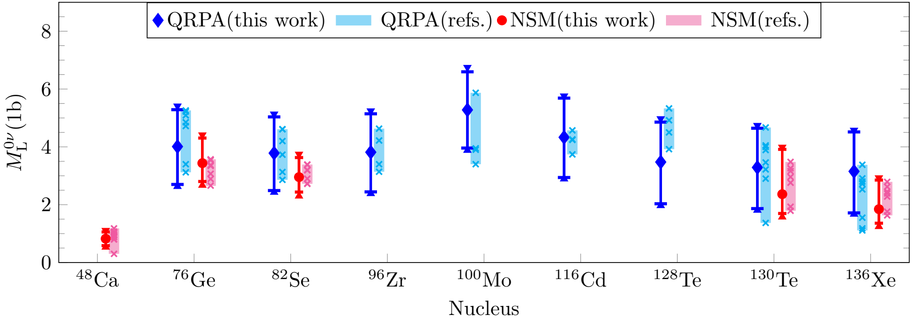


$0\nu\beta\beta$ NMEs from $2\nu\beta\beta - 0\nu\beta\beta$ correlation

NMEs consistent with previous nuclear shell model, QRPA results

Theoretical uncertainty involves
systematic calculations covering dozens of nuclei and interactions
error of each calculation (eg quenching) and experimental $2\nu\beta\beta$ error

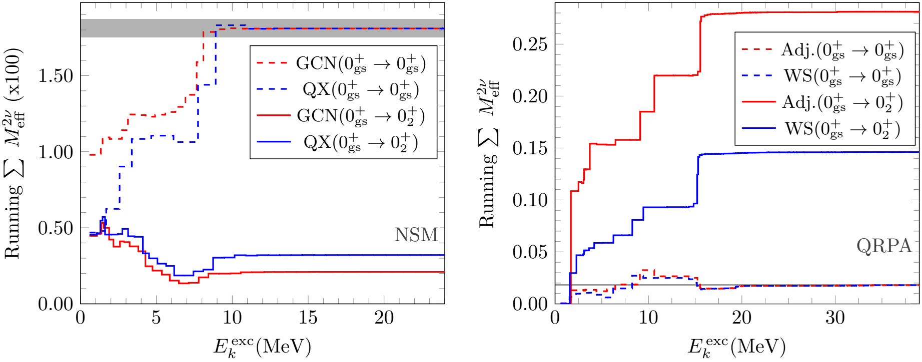
Previous theoretical uncertainty mostly ignored: collection of calculations



Jokiniemi, Romeo, Soriano, JM, PRC 107 044305 (2023)

^{136}Xe $\longrightarrow$ ^{136}Ba 0_2^+ running sums

Subtle cancellation NME running sum, depends on many-body method



Jokiniemi, Romeo, Brase, Kotila et al. PLB 838 137689 (2023)

Shell-model running sum shows cancellations in decay to ground state

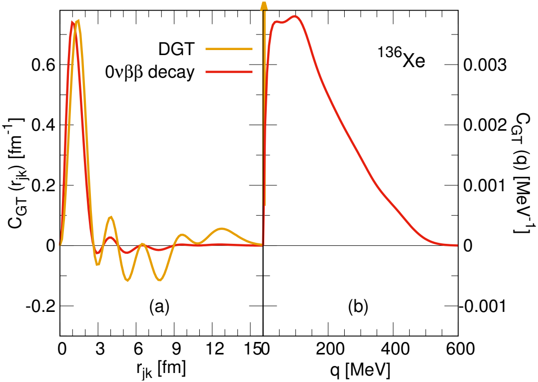
QRPA running sum shows cancellations in decay to excited state

Since ground-state decay fitted to data, very different decay to excited state

Short-range character of DGT, $0\nu\beta\beta$ decay

Correlation between DGT and $0\nu\beta\beta$ decay matrix elements explained by transition involving low-energy states combined with dominance of short distances between exchanged/decaying neutrons

Bogner et al. PRC86 064304 (2012)



$0\nu\beta\beta$ decay matrix element limited to shorter range

Short-range part dominant in double GT matrix element due to partial cancellation of mid- and long-range parts

Long-range part dominant in QRPA DGT matrix elements

Shimizu, JM, Yako, PRL120 142502 (2018)

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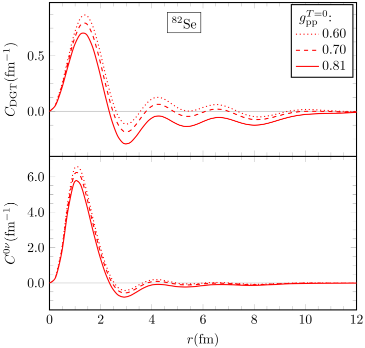

Jokiniemi, JM, PRC 107 044316 (2023)

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Long-range part dominant in QRPA DGT matrix elements

Shimizu, JM, Yako,
PRL120 142502 (2018)

Short-range NME: relative impact

Modified decay rate: $T_{1/2}^{-1} = G_{01}\, g_A^4 \left(M^{0\nu}_{\text{long}} + M^{0\nu}_{\text{short}}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$

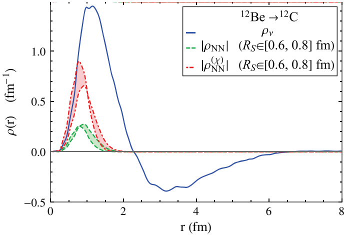
Assume $g_\nu^{NN} \sim 1\text{fm}^2$

Cirigliano et al.
PRC100 055504 (2019)

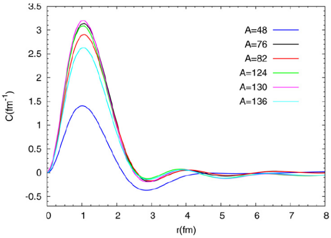
TABLE II. Values of $\mathcal{C}_1 + \mathcal{C}_2$ obtained from the CIB contact interactions in various chiral potentials.

Model	Ref.	R_S (fm)	C_0^{IT} (fm^2)	$(\mathcal{C}_1+\mathcal{C}_2)/2$ (fm^2)	Model	Ref.	Λ (MeV)	$(\mathcal{C}_1+\mathcal{C}_2)/2$ (fm^2)
NV-Ia*	[38]	0.8	0.0158	−1.03	Entem-Machleidt	[34]	500	−0.47
NV-IIa*	[38]	0.8	0.0219	−1.44	Entem-Machleidt	[34]	600	−0.14
NV-Ic	[38]	0.6	0.0219	−1.44	Reinert *et al.*	[39]	450	−0.67
NV-IIc	[38]	0.6	0.0139	−0.91	Reinert *et al.*	[39]	550	−1.01
					NNLO_{sat}	[37]	450	−0.39

$\sim$ 75% correction for QMC ^{12}Be NME
In heavy nuclei, less severe cancellation of dominant $M^{0\nu}$?



Cirigliano et al. PRL120 202001(2018)



JM et al. NPA818 139 (2009)

2b currents in $0\nu\beta\beta$ decay

In $0\nu\beta\beta$ decay, two weak currents lead to four-body operator when including the product of two 2b currents: computational challenge

Approximate 2b current as effective 1b current normal ordering with respect to a Fermi gas

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Gysbers et al. Nature Phys. 15 428 (2019)

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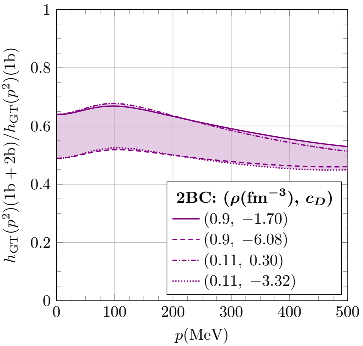
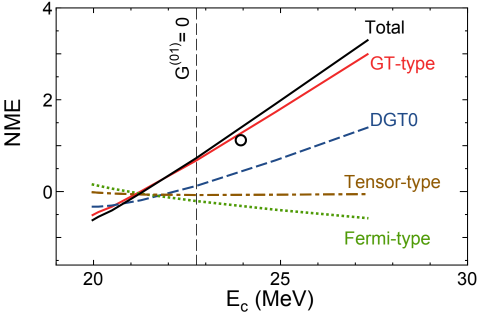
Hoferichter, JM, Schwenk PRD102 074018 (2020)



Jokiniemi, Romeo, Soriano, JM, PRC 107 044305 (2023)

^{48}Ca double GT giant resonance and $0\nu\beta\beta$ decay

Correlation between Double Gamow-Teller resonance in ^{48}Ca and $0\nu\beta\beta$ decay nuclear matrix element



Shimizu, JM, Yako, PRL120 142502 (2018)

Energy of DGT resonance with accuracy to $\sim$1MeV, can give insight on value of $0\nu\beta\beta$ decay matrix element

$$E_c = \frac{\sum_f E_f B(DGT^-, i \to f)}{\sum_f B(DGT^-, i \to f)}$$

Good test of nuclear structure calculation

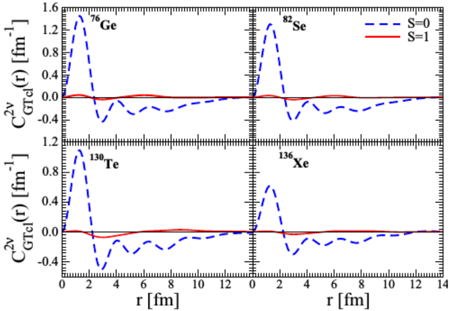
Relatively consistent with *sdpf* calculation (open circle)

Contribution of $S = 1$ pairs to DGT NME

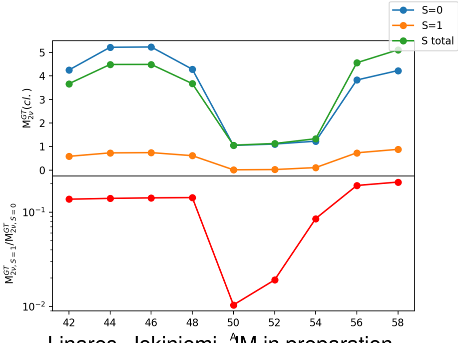
NMEs are dominated by $S = 0$ pairs

In DGT QRPA, $S = 1$ pair contributions extremely suppressed
lead to small $M^{DGT} = M^{DGT}_{S=0} + M^{DGT}_{S=1} = 4M^{DGT}_{S=1}$ (isospin conserved)

In contrast, nuclear shell model $M^{DGT}_{S=1}$ small but not negligible,
understood in terms of broken SU(4) symmetry in nuclei



Šimkovic, Smetana, Vogel PRC98 064325(2019)

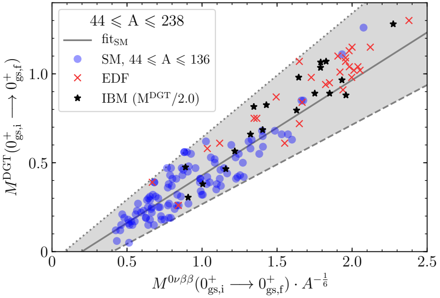


Linares, Jokiniemi, JM in preparation

$0\nu\beta\beta$ decay NMEs in EFT of β decay

Effective field theory of β decay can calculate DGT with uncertainties
(similar to calculation of $2\nu\beta\beta$, no energy denominator)
DGT vs 0nbb correlation $\Rightarrow$ predict $0\nu\beta\beta$ NMEs with uncertainties

Because EFT couplings fitted to β decay and GT strengths
shell-model DGT NMEs in correlation need "quenching": $q = 0.42 - 0.65$



As a result, ET $0\nu\beta\beta$ NMEs
^{76}Ge: $M^{0\nu} = 0.2 - 2.4$
^{82}Se: $M^{0\nu} = 0.2 - 2.7$

small NMEs

large uncertainty:
LO in ET, fit, "quenching"

Brase, Coello Pérez, JM, Schwenk
PRC106 034309(2022)

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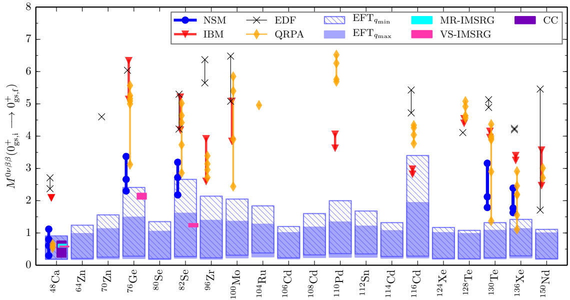
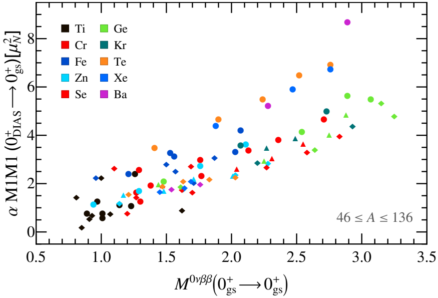


Brase, Coello Pérez, JM, Schwenk, PRC106 034309 (2022)

Intermediate states of the $M1M1$ transition

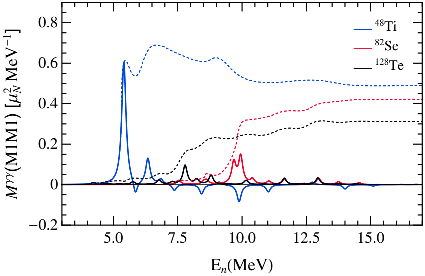


When energy denominators are (artificially) removed, same correlation across the nuclear chart

Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

Dominant intermediate states lower energies for lighter nuclei, otherwise similar energies

One or few intermediate states typically dominate the transition

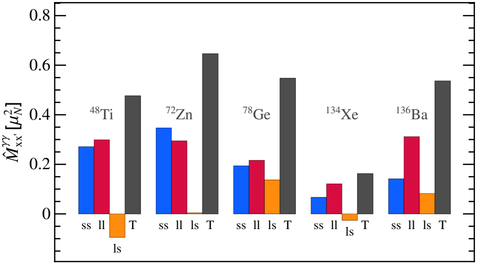


Spin, angular momentum decomposition

The numerator NME can be decomposed into

$$\hat{M}_{\gamma\gamma} = \hat{M}_{ss} + \hat{M}_{ll} + \hat{M}_{ls}$$

spin, angular momentum and interference components



Spin, angular momentum terms
strikingly similar,
always carry same sign

Interference term
can cancel the other two
but always much smaller

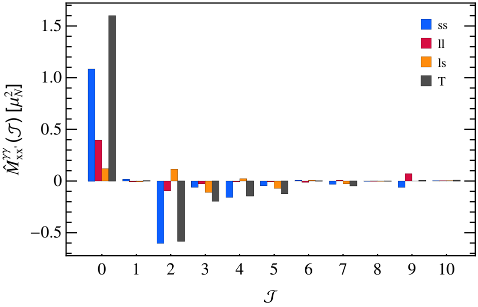
Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

Total angular momentum decomposition

The numerator NME can be decomposed into

$$\hat{M}_{\gamma\gamma}(\mathcal{J}) = \hat{M}_{ss}(\mathcal{J}) + \hat{M}_{ll}(\mathcal{J}) + \hat{M}_{ls}(\mathcal{J})$$

spin, angular momentum and interference components
and total angular momentum of the nucleons involved in the transition



Dominance of $\mathcal{J} = 0$ terms
for spin and orbital contributions
just like in $0\nu\beta\beta$ decay

Cancellation from $\mathcal{J} > 0$ terms
less pronounced in orbital part

Explains similar behaviour of spin
and orbital components:

$$s_1\, s_2 = \mathcal{S}^2 - 3/2 < 0$$

$$l_1\, l_2 = \mathcal{L}^2 - l_1^2 - l_2^2 < 0$$

Romeo et al. PLB 827 136965 (2022)

Nuclear matrix elements for new-physics searches

Neutrinos, dark matter studied in experiments using nuclei

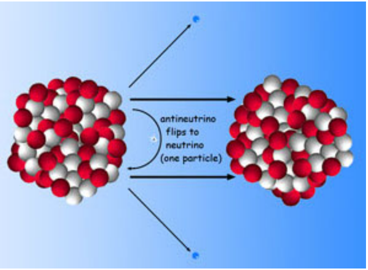
Nuclear structure physics
encoded in nuclear matrix elements
key to plan, fully exploit experiments

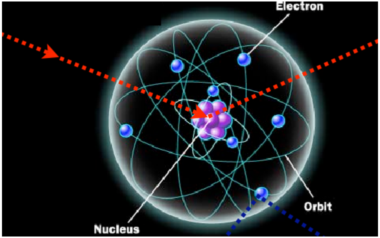
$$0\nu\beta\beta\text{: } \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4 \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

$$\text{Dark matter: } \frac{d\sigma_{\chi\mathcal{N}}}{d\boldsymbol{q}^2} \propto \left|\sum_i c_i \zeta_i \mathcal{F}_i\right|^2$$

$$\text{CE}\nu\text{NS: } \frac{d\sigma_{\nu\mathcal{N}}}{d\boldsymbol{q}^2} \propto \left|\sum_i c_i \zeta_i \mathcal{F}_i\right|^2$$

$M^{0\nu\beta\beta}$: Nuclear matrix element
$\mathcal{F}_i$: Nuclear structure factor





Systematic shell-model calculations

Explore systematic shell-model matrix elements
in configuration spaces relevant for $0\nu\beta\beta$ decay searches

- $^{46-58}$Ca, $^{50-58}$Ti, and $^{54-60}$Cr
  in pf-shell with KB3G and GXPF1B interactions
- $^{72-76}$Ni, $^{74-80}$Zn, $^{76-82}$Ge, and ^{82,84}Se
  in $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$, and $0g_{9/2}$ configuration space
  with GCN2850, JUN45, and JJ4BB interactions
- $^{124-132}$Sn, $^{130-134}$Te, and ^{134,136}Xe
  in $1d_{5/2}$, $0g_{7/2}$, $2s_{1/2}$, $1d_{3/2}$, and $0_{h11/2}$ configuration space
  with the GCN5082 and QX interactions

Overall, $\sim 20-40$ different calculations for each configuration space

Complementary approach to randomly varying nuclear interaction
Horoi et al. PRC106 054302 (2022), PRC107 045501 (2023)

2b currents in $0\nu\beta\beta$ decay

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Approximate 2b current as effective 1b current normal ordering with respect to a Fermi gas

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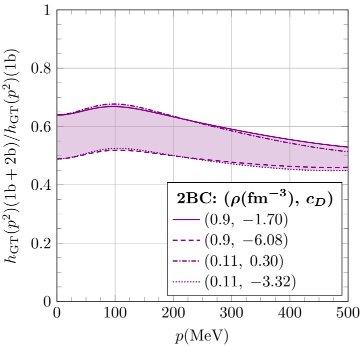
Hoferichter, JM, Schwenk

PRD102 074018 (2020)

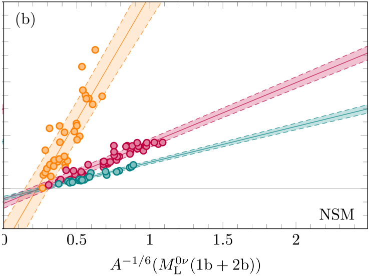


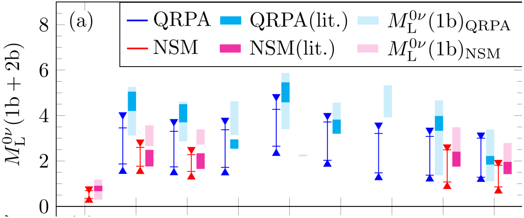
Jokiniemi, Romeo, Soriano, JM

PRC 107 044305 (2023)

Correlation of $0\nu\beta\beta$ decay to $2\nu\beta\beta$: 2b currents

Good correlation between $2\nu\beta\beta$ and $0\nu\beta\beta$
also present when including 2b currents to the $0\nu\beta\beta$ NMEs





Jokiniemi, Romeo, Soriano, JM, PRC 107 044305 (2023)

Use $2\nu\beta\beta$ data to predict $0\nu\beta\beta$ NMEs with 2b currents

Light-neutrino exchange: contact operator

Short-range operator contributes to light-neutrino exchange
for RG invariance of two-nucleon decay amplitude: high-energy ν's

$$T_{1/2}^{-1} = G_{01}\, g_A^4 \left(M^{0\nu}_{\text{long}} + M^{0\nu}_{\text{short}}\right)^2 m_{\beta\beta}^2,$$ Cirigliano et al. PRL120 202001(2018)

$$M^{0\nu}_{\text{short}} \equiv \frac{1.2 A^{1/3}\,\text{fm}}{g_A^2} \langle 0_f^+ | \sum_{n.m} \tau_m^- \tau_n^- \, \mathbb{1} \left[\frac{2}{\pi} \int j_0(qr)\, 2 g_\nu^{\text{NN}}\, g(p/\Lambda)\, p^2 dp\right] | 0_i^+ \rangle,$$

$$M^{0\nu}_{\text{GT}} \simeq \frac{1.2 A^{1/3}\,\text{fm}}{g_A^2} \langle 0_f^+ | \sum_{n.m} \tau_m^- \tau_n^- \, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \left[\frac{2}{\pi} \int j_0(qr)\, \frac{1}{p^2}\, g_A^2\, f^2(p/\Lambda_A)\, p^2 dp\right] | 0_i^+ \rangle$$

Unknown value (and sign) of the hadronic coupling g_ν^{NN}!

Lattice QCD calculations can obtain value of g_ν^{NN}

Davoudi, Kadam, Phys. Rev. Lett. 126, 152003 (2021), PRD105 094502('22)

match $nn \to pp + ee$ amplitude calculated with dispersion QCD methods

Cirigliano et al. PRL126 172002 (2021), JHEP 05 289 (2021)

charge-independence breaking of nuclear Hamiltonians

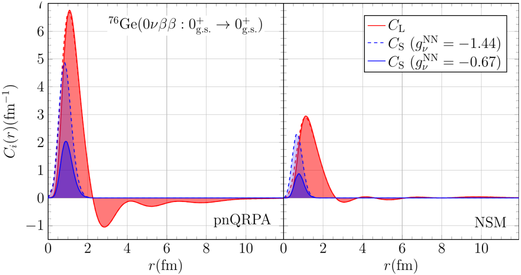
Cirigliano et al. PRC100, 055504 (2019)

Long and short-range NME in heavy nuclei

Relatively stable contribution of new term M_S/M_L:

$20\% - 50\%$ impact of short-range NME in shell model
$30\% - 70\%$ impact of short-range NME in QRPA

consistent with 43% effect in IM-GCM for ^{48}Ca
using calculated $nn \to pp + ee$ decay Wirth et al. PRL127 242502 (2021)



Jokiniemi, Soriano, JM, Phys. Lett. B 823 136720 (2021)

Uncertainty dominated by coupling g_ν^{NN}

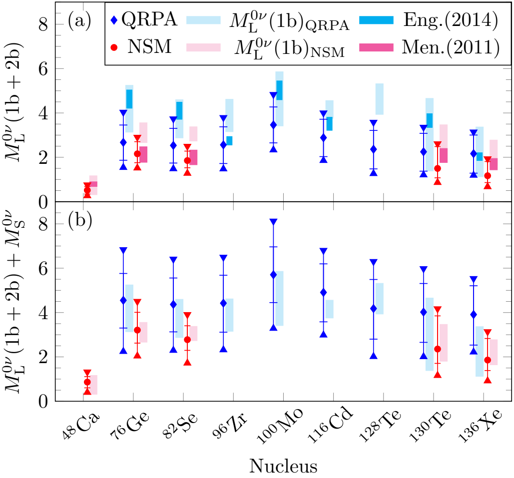
$0\nu\beta\beta$ NMEs from correlation: 2bc, short-range

$0\nu\beta\beta$ NMEs including 2b currents and short-range NME obtained from $0\nu\beta\beta - 2\nu\beta\beta$ correlation and $2\nu\beta\beta$ data

Theoretical uncertainty due to correlation,
calculation uncertainties: quenching, 2bc, short-range NME coupling (dominant uncertainty)

First complete estimation of $0\nu\beta\beta$ nuclear matrix elements with theoretical uncertainties

Jokiniemi, Romeo, Soriano, JM, PRC 107 044305 (2023)

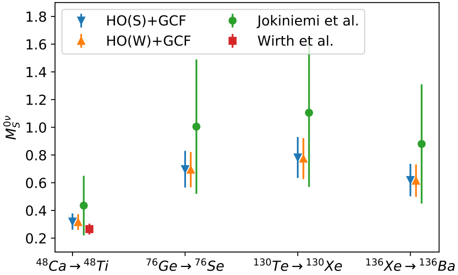


Short-range NME: GCF + shell model

Shell model with short-range correlations from QMC using the GCF give consistent contribution of new term M_S

$\sim$ 25% impact of short-range NME in GCF + shell model obtained with $g_\nu^{\rm NN}$ from AV18 CIB term

consistent with 43% effect in IM-GCM for ^{48}Ca using calculated $nn \to pp + ee$ decay Wirth et al. PRL127 242502 (2021)



Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)